THE DESIGN AND CONSTRUCTION OF
A FREQUENCY STANDARD SYSTEM

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by

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A FREQUENCY STANDARD SYSTEM

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ACKNOWLEDGMENTS

On the completion of this work I wish to express my sincerest thanks to Dr. W. A. Edson, not only for his suggestion of the problem, but also for his most valuable aid and guidance in its prosecution. I should also like to thank Professor M. A. Honnell for helping me to solve numerous construction problems.

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INTRODUCTION

Development in communication engineering depends largely upon precise measurements. In order that these may be made, we must have standards which are accurate to a degree equal to or better than the measurements which we may wish to make. One of the most important standards is that of frequency. The improvements in frequency standardization clearly reflect the advances made in radio and communications engineering.

In 1925 international frequency measurements agreed only to within plus or minus one part in a thousand. In contrast many applications today require a stability of one part in ten million over a period of a day, and absolute standards are known to one part in a hundred million.

Since frequency may be expressed in terms of time as

$$F = \frac{1}{T} \tag{1}$$

where T is the period of one cycle of oscillation, the measurement of frequency involves counting the cycles of oscillation which have occurred in a measured time. The ultimate standard of frequency is the same as that of time, and is provided by the rotation of the earth once per sidereal day. An absolute standard of frequency, therefore, is calibrated in terms of the earth's rotation, and comprises a stable oscillator with associated apparatus whereby the number of cycles of oscillation may be counted. "Unfortunately," according to Booth and Laver,[1] "the earth's rotational period is known to be affected by cyclical variations of the axis of rotation about its mean position, by the perturbing effects of other members of the solar system, and by the retardation due to tidal friction. Additionally, unpredictable changes of the order of plus or minus four parts in a hundred million have been detected on rare occasions, and these changes set a limit to the use of the earth as a standard." Despite these variations, the earth is a better timekeeper than any purely mechanical devices yet developed, i.e., pendulum clocks. It has been only through recent development of quartz crystal oscillators that devices have been built which have a more accurate long-time frequency stability than that of the earth.

The principal technical factors controlling the design of a frequency standard are:

(a) The base frequency to be used
(b) The range of frequencies to be covered
(c) The accuracy required
(d) The frequency stability of the available oscillators
(e) The accuracy of calibration

The primary objective of this thesis was the design and construction of a frequency standard which would have a stability approaching one part in a million for use in the electronics laboratory of the Electrical Engineering Department of the Georgia School of Technology.

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[1] C. F. Booth and F. J. M. Laver, "A Standard of Frequency and Its Applications," Journal of the Institute of Electrical Engineers, Vol. 93, Pt. III, pp. 223-41.

A secondary objective consisted in the development of a counting device suitable for comparing the frequency of this standard with that of the frequency standard of the National Bureau of Standards, Washington, D. C.

The standard frequency for precision methods of frequency measurement is generally derived from a piezoelectric oscillator. These oscillators usually operate in the range of 50 to 100 kc because it has been found that the greatest degree of stability can be obtained at these frequencies.[2] Therefore, 100 kc was decided upon as a desirable frequency for our use.

The circuit which seemed most suitable for a 100 kc frequency standard is the Meacham Bridge Oscillator.[3] This circuit was chosen because it is capable of sustaining stable oscillations with a variation as little as one cycle in a hundred million over a long period of time.

Since frequency division has long been successfully accomplished by the use of multivibrators, these circuits have been incorporated in the frequency standard to reduce the frequency to 50 cycles so that a synchronous motor driven clock may be used to count the cycles of oscillation. In addition a 2,000 cycle signal from the multivibrators will be used to compare with the 4,000 cycle tone broadcast by radio station WWV of the Bureau of Standards so that short-time checks of frequency may be made. A block diagram of the frequency standard system is shown

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[2]H. O. Peterson and A. M. Braaten, "The Precision Frequency Measuring System of RCA Communications, Inc.," Proc. I. R. E., Vol. 20, 1932, p. 941.

[3]L. A. Meacham, "The Bridge-Stabilized Oscillator," Proc. I. R. E., Vol. 26, 1938, p. 1278.

in Figure 1.

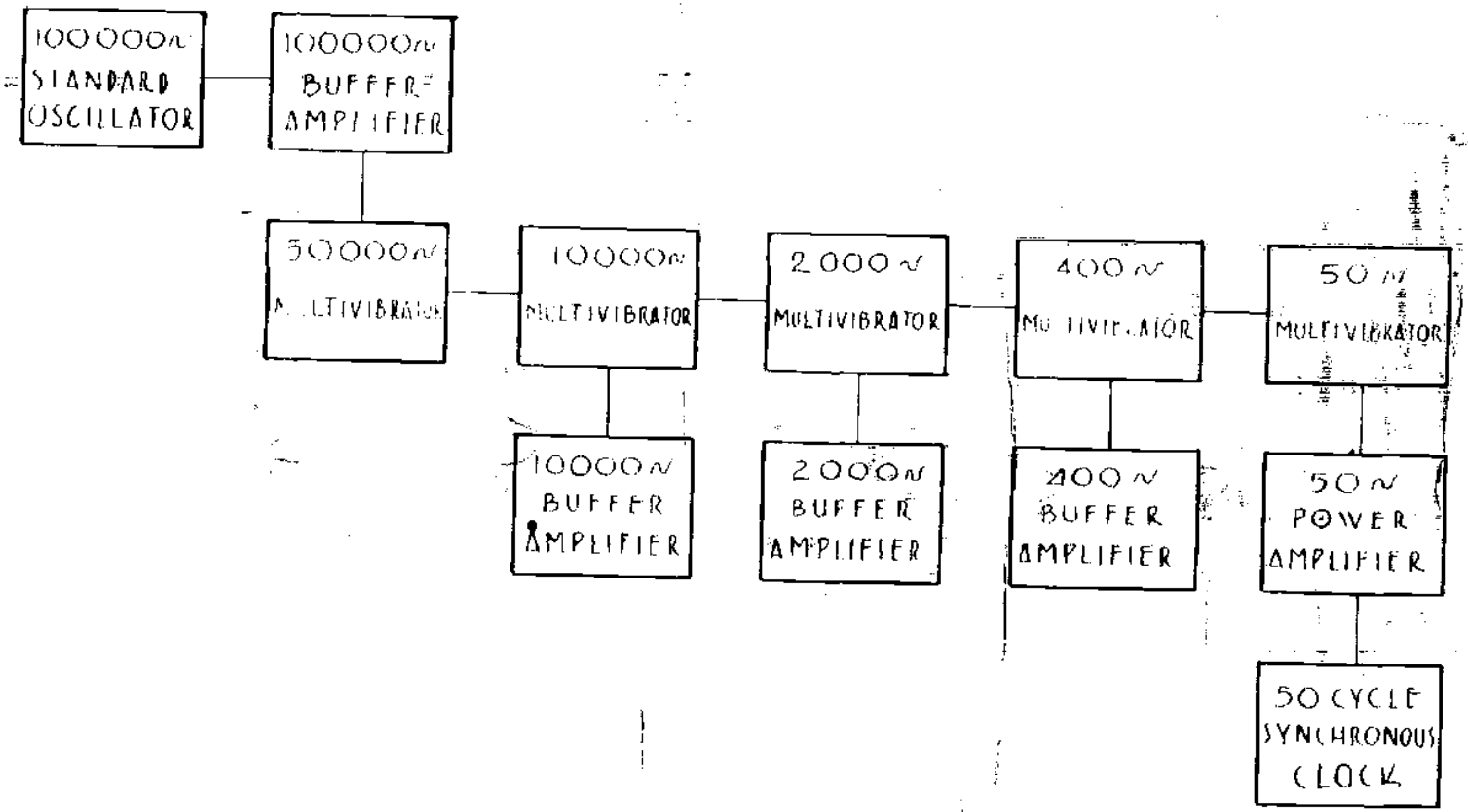

FIGURE 1
FREQUENCY STANDARD SYSTEM - BLOCK DIAGRAM

THE 100 KC OSCILLATOR

The Meacham oscillator employs a simple linear amplifier of one, two, or even three stages, depending upon the gain that is desired. The output of the amplifier is fed to a special form of Wheatstone bridge whose conjugate terminals are connected to the input of the amplifier. Hence, the output of the amplifier is attenuated by the bridge which in turn serves as a source of feed-back to the input.

The very excellent performance of this circuit results from the fact that the bridge functions both as a limiter and as the frequency determining device. The frequency is determined by a quartz crystal placed in one arm of the bridge while the limiting action is due to a thermistor in the opposite arm of the bridge. The other two arms are both fixed resistors. Because of the limiting action, the operation of the oscillator is entirely linear and the harmonic output is very small. In addition to providing for constancy of output and purity of wave form the bridge also provides stabilization against fluctuations in power supply or changes in circuit elements.[4]

In designing the amplifier portion of the Meacham oscillator several points had to be considered, namely:

(1) The gain desired
(2) Type of inter-stage coupling
(3) Input and output circuits
(4) Security from spurious oscillations

It was decided that a gain of 60 db in the amplifier would be desirable to obtain a sufficiently high degree of oscillator stability.

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[4] Ibid.

Therefore, a two stage amplifier was designed such that each stage had a gain of approximately 30 db. Both stages employ 6SJ7 pentodes operating class A_1. The first stage is impedance coupled to the second stage by a coil with sufficient inductance to resonate the stray capacitance. A resistance is shunted across the plate load in order to broaden the coupling as much as possible. The second stage is loaded with a tuned circuit, the inductance of which is the high impedance side of an iron core transformer which gives a voltage step-down and corresponding current increase to the bridge input. The high impedance side of this transformer has capacitive tuning while the low side is untuned. The output of the bridge is fed to a resonant, inductance-capacitance network designed to give a voltage gain of approximately 30. The output of this network is then fed to the input of the first stage.

To insure against spurious oscillations in the amplifier, the output transformer is constructed with electrostatic shielding between primary and secondary windings. This shielding causes the output of the transformer to be approximately balanced to ground. In addition the cathode resistors are not by-passed, thus allowing cathode degeneration of the order of 4 to 1 in each stage.

As described above, the Meacham oscillator consists fundamentally of an amplifier and a Wheatstone bridge and is shown in the simplified schematic of Figure 2, page 11. Arm AB is a series resonant RLC circuit and may be used to represent the equivalent circuit of a quartz crystal when vibrating at its natural series resonant frequency. This arm is the frequency controlling element of the Meacham oscillator. A parallel resonant circuit could be used instead, if its position in the bridge were interchanged with either of the two fixed resistors. This is usually undesirable, however, as the use of a series resonant circuit has the advantage of minimizing the effects of stray capacitance because of the necessarily low impedance level.

Arm CD contains a thermistor whose resistance increases when an increase in current causes it to rise in temperature. Any thermistor used in arm CD must have a positive temperature-resistance coefficient, but it would be possible to use a negative coefficient thermistor if its position were interchanged with either of the two fixed resistors. The choice in this case was determined by the convenience of a small tungsten filament switchboard lamp which has a current-resistance characteristic ideally suited for this purpose.

In the steady state condition the bridge is very close to balance. If we assume that R_1, R_2, and R_4 are pure resistances, then for exact reactive balance

$$X_3 = 0 \qquad (2)$$

and for exact resistance balance

$$\frac{R_1}{R_3} = \frac{R_2}{R_4} \qquad (3)$$

In order that the circuit may oscillate, a slight unbalance is necessary; therefore, R_2 must have a value such that

$$\frac{R_1 R_4}{R_3} > R_2 \qquad (4)$$

It can be seen that if all the bridge arms had fixed values of resistance, the attenuation of the bridge would change greatly with slight changes in any arm. Thus, either oscillations would not occur, or else they would build up until the amplifier was overloaded. The thermistor, R_2, overcomes this difficulty because of its aforementioned large positive temperature-resistance coefficient. The bridge is so designed that the current through this arm is sufficient to raise its temperature and increase its resistance materially.

When the plate supply is first applied to the amplifier, the thermistor is cold and its resistance is much smaller than that necessary to balance the bridge. Consequently the attenuation of the bridge is quite low and oscillations build up rapidly once they are initiated by thermal noise or plate supply transients. As the amplitude of oscillation increases, the lamp heats up and its resistance approaches the value required for balance. If the resistance of the thermistor overshoots the desired value, the unbalance potential "e" becomes too small or possibly inverted in phase, so that the amplitude decreases until the proper equilibrium is reached.

This automatic adjustment stabilizes the amplitude, because the amount of power needed to give R_2 a value closely approaching R_1R_4/R_3 is always very nearly the same. The percentage change of R_2 is quite small. It is to be noted that the heating cycle of the thermistor is long as compared to the period of oscillation. Also, the operating temperature of the lamp is made high enough so that variations in the ambient temperature do not affect the adjustment appreciably.

Thus far we have stated that the bridge will reach equilibrium at a point just below that of resistive balance. Now this equilibrium point is actually determined by the gain of the amplifier. This we know to be true and can prove by the Nyquist criterion for oscillation[5] which states that for constant amplitude the vector product of μ and β must be equal to unity where

μ equals the vector amplification
β equals the vector feedback

Therefore, the attenuation of the bridge must equal the amplification of the amplifier and its phase shift must be equal and opposite to that of the amplifier. This leads us to the most convenient explanation of the behavior of the Meacham oscillator.[6,7] The bridge acts to magnify the phase shift of the crystal by an enormous amount so that a relatively large phase shift in the amplifier can be balanced by a very small phase shift in the crystal arm of the bridge. This phase shift in the crystal is caused by a proportionately small frequency shift. This is equivalent to a magnification or increase in the effective value of the Q of the crystal.

Let us consider the simplified Meacham oscillator of Figure 2 and its associated vector diagrams. We will make the valid assumption that the output current of the bridge is small compared to the arm currents of the bridge.

First consider the case where the frequency of oscillation is exactly that to which the crystal or tuned circuit is series resonant.

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[5]H. Nyquist, "Regeneration Theory," Bell System Tech. Jour., Vol. II, 1932, p. 126.

[6]W. A. Edson, "Vacuum Tube Oscillators," Unpublished notes, Electrical Engineering Department, Georgia School of Technology, 1947, p. 172.

[7]See Appendix I.

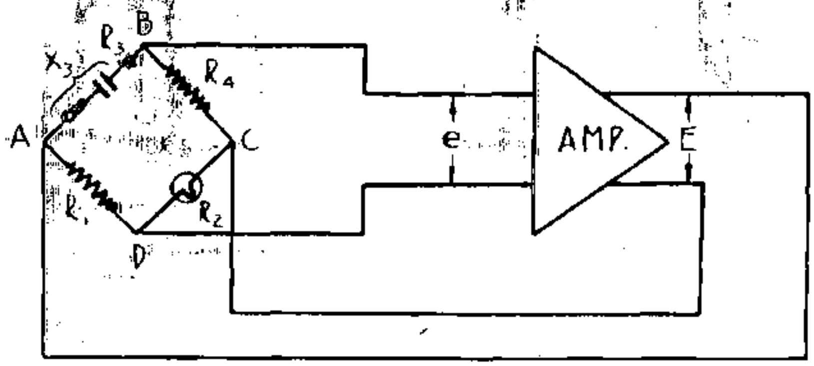

FIGURE 2
SIMPLIFIED MEACHAM OSCILLATOR

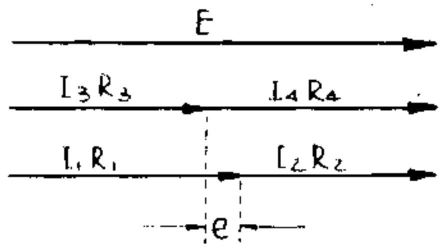

FIGURE 3

VECTOR DIAGRAM OF BRIDGE VOLTAGES
AT RESONANT FREQUENCY

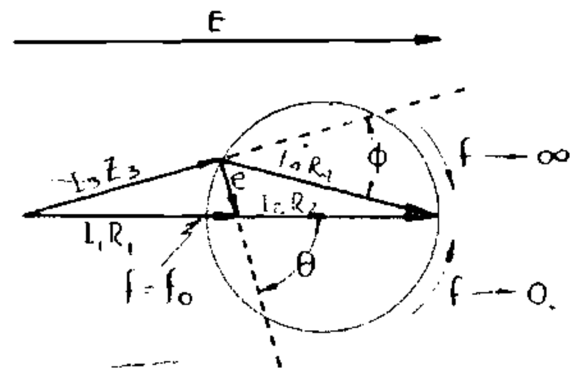

FIGURE 4

VECTOR DIAGRAM OF BRIDGE VOLTAGES
AT A FREQUENCY GREATER THAN RESONANCE

The bridge then is purely resistive and its various voltages can be represented by the vector diagram of Figure 3.

In Figure 3, "E" is the output voltage of the amplifier and the input voltage to the bridge while "e" is the output of the bridge and the input to the amplifier. It can be seen that for oscillations to occur, the bridge must not be balanced, otherwise, there would be no input to the amplifier.

Next let us examine the bridge when the frequency of oscillation is slightly above that of crystal resonance. Under this condition Z_3 is inductive and hence the voltage across the crystal arm must lead that in the purely resistive branches. This is illustrated in Figure 4.

Under these conditions the input voltage "e" must shift in phase by the angle θ in order to maintain the zero net phase shift, which is necessary for oscillation, around the loop. If a tuned circuit were being employed without a bridge, then the resonant element would have to shift its phase by θ degrees and consequently its frequency by a corresponding amount. However, when the resonant element is placed in the bridge circuit, the required phase shift of θ degrees in the bridge output is accomplished by a much smaller phase shift, ϕ, in the resonant element. It is to be noted that Figure 4 is greatly expanded for clarity and does not correctly show the relative values of θ and ϕ. As stated before in order that $\mu\beta$ equal to 1, the attenuation of the bridge must equal the gain of the amplifier. In other words, with an amplifier having a gain of 60 db, the ratio of "E" to "e" will be 1,000 and a vector diagram drawn to scale would show "E" to be 1,000 times longer than the real component of "e". Obviously the ratio of θ to ϕ will be correspondingly large.

Since a relatively large phase shift in the bridge output voltage can be accomplished with a small phase change in the resonant element, the frequency of oscillation is almost totally independent of everything except the resonant frequency of the tuned arm.

The analysis for frequencies below resonance is similar to that given above. The vector diagram will be the same only inverted with the locus of the tail of "e" being the lower semi-circle as "f" approaches zero.

In order that the extremely stable oscillations of the Meacham circuit may be used as a frequency standard, means must be had for obtaining some of this energy for comparison purposes without disturbing the circuit. For this purpose a high-gain buffer amplifier is capacity coupled to the output of the first stage of amplification. The gain of this amplifier is so adjusted that its output is of the proper magnitude to synchronize the first multivibrator of the frequency division system.

THE FREQUENCY MEASURING SYSTEM

In order to maintain a precise check on the accuracy of the 100 kc standard oscillator it was decided that facilities for both long and short time frequency comparisons should be included in the system. The simplest method for obtaining the latter is to generate a frequency which is an exact integral fraction of the standard oscillator frequency and which may be compared with one of the standard tones as broadcast by the Bureau of Standards' station WWV. Therefore, it was decided to synchronize a 2,000 cycle multivibrator with the 100 kc oscillator and compare this signal with the 4,000 cycle tone of WWV by means of an oscilloscope.

The most direct method of obtaining a long time check is to drive an electric clock by a voltage having a frequency which is an integral fraction of the standard. For this purpose a two watt, 50 cycle, synchronous clock was obtained.

In addition to the necessary 50 and 2,000 cycles, it was considered desirable to have available also frequencies of 10,000 and 400 cycles for further measuring purposes.

In order to obtain the frequencies listed above, frequency division by some reliable method is necessary. Multivibrators were chosen for this function because they afford an easily constructed and relatively dependable frequency division system.

Since division by integral numbers has been shown to be more stable than division by fractions,[8] the 10,000 cycle output was obtainable only by dividing by two and five. The first division ratio was made

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[8]V. J. Andrew, "The Adjustment of a Multivibrator for Frequency Division," Proc. I. R. E., Vol. 19, 1931, p. 1911.

two and the second five because division by large numbers is somewhat more reliable at lower frequencies. Consequently, the first multivibrator in the chain operates at 50 kc and the second at 10 kc. The 2 kc signal is now readily obtained by again dividing by five; while a third division by five produces the 400 cycle signal. The 50 cycle output is accomplished by a final division by eight.

On the same chassis with the five multivibrators there are four amplifiers; namely, three buffer amplifiers for supplying 10,000, 2,000, and 400 cycle outputs, and a power amplifier operating at 50 cycles to drive the clock.

The Free-running Multivibrator

Before discussing the operation of synchronized multivibrators, it will be well to review some of the actions of free-running multivibrators.[9,10,11]

Consider the symmetrical multivibrator of Figure 5. The cycle of operation is as follows. When the plate supply voltage is switched on plate current begins to flow in both tubes, but since no two tubes are identical in construction, the plate currents cannot continue to increase equally. Therefore, let us assume that in this case the current in tube 1 increases faster than that of tube 2. The voltage drop across

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[9]E. R. Shenk, "Multivibrator, Applied Theory and Design," Electronics, Vol. 17, 1944, p. 136.

[10]Radar Electronic Fundamentals, Navships 900,016, Bureau of Ships, Navy Department, 1944, pp. 192-205.

[11]M. V. Kiebert, Jr. and A. F. Inglis, "Multivibrator Circuits," Proc. I. R. E., Vol. 33, 1945, p. 534.

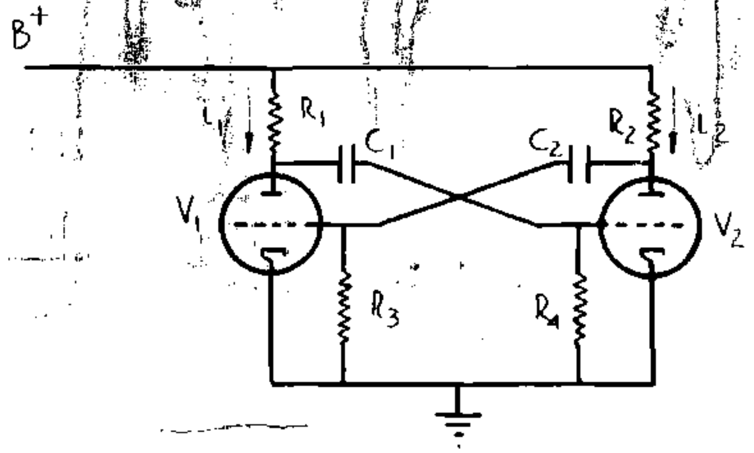

FIGURE 5

FREE-RUNNING MULTIVIBRATOR CIRCUIT

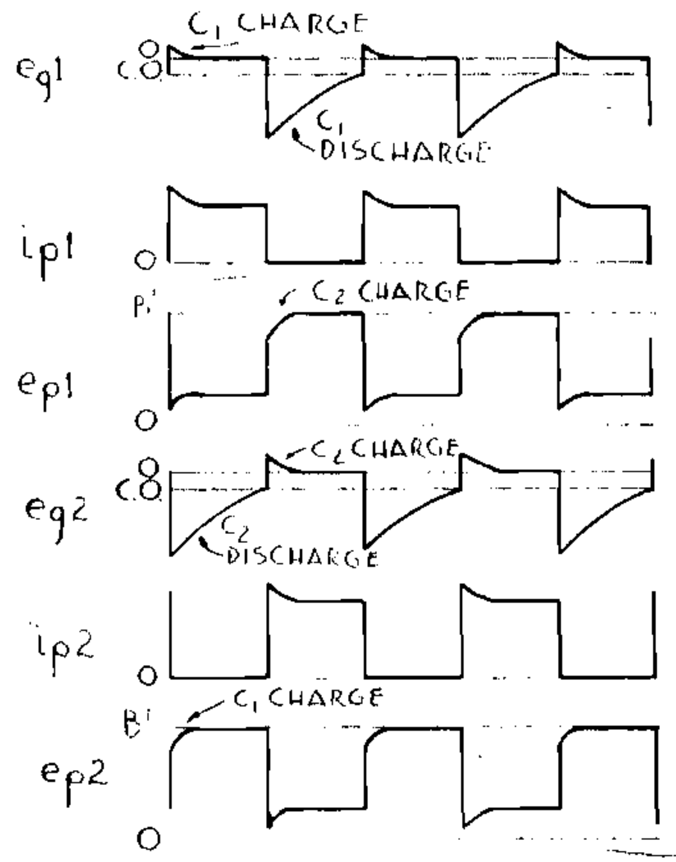

FIGURE 6

WAVE FORMS IN A BALANCED FREE-RUNNING MULTIVIBRATOR the resistor, R_1, will then increase more rapidly than that across R_2. Consequently, the potential of the plate of tube 1 will decrease, carrying with it the grid of tube 2, because the voltage across C_2 cannot change instantly. This decrease in the grid voltage of tube 2 causes a corresponding decrease in the plate current of that tube, thus allowing i_1 to become even larger than i_2. This effect is cumulative and continues until tube 2 is cut off. In order to cut off the plate current in this tube its grid must be driven negative beyond the cut-off voltage. The negative grid voltage results from the voltage across the condenser C_2.

It is to be remembered that the switching action described above occurs almost instantaneously; the exact time being determined principally by the interelectrode capacitance and the plate load resistor.

Tube 2 will now continue cut off until enough charge leaks off C_2 to allow the grid voltage to become less negative than the cut-off value. This charge may leak off by way of the grid-leak resistor, R_4, which is in series with the parallel combination of the plate resistance of tube 1 and R_1. The time of this discharge may be computed by the following equation which is based on the exponential flow of current in an RC circuit.

$$t = RC \log_e \frac{E_x}{E_y} \qquad (5)$$

In this equation t is the time in seconds required for the voltage on the grid of tube 2 to rise from the large negative value to which it was driven by the conduction of tube 1, to the cut-off voltage of the tube. R is the resistance of the discharge path, or

$$R = R_4 + \frac{r_p R_1}{r_p + R_1} \qquad (6)$$

E_x is the voltage to which the grid was driven and E_y is the cut-off voltage of the tube. C equals C_2 and r_p is the plate resistance of each tube. In the usual case R_4 is considerably larger than either r_p or R_1 and its value alone may be used for approximate calculations of t.

Thus far we have considered the effect of conduction in tube 1 on tube 2. When the grid voltage of tube 2 reaches cut-off, then conduction takes place in tube 2. This is the beginning of a cumulative switching action identical with that described above. If we assume that the time of switching is almost instantaneous, the time of one period of the multivibrator will be the sum of the discharge times of the two condensers. The plate and grid voltages wave forms of a typical symmetrical multivibrator are shown in Figure 6, page 16.

The above multivibrator is known as the grounded grid return type because the grid-leaks of both tubes are returned to the cathode. On examining equation (5) it will be seen that E_x and E_y are both potential differences; specifically, E_x is the difference between the original voltage across the condenser and that towards which it is discharging, and E_y is the difference between the voltage at the end of the period in question and that towards which it is discharging. By the very nature of the exponential curve, as shown in Figure 7, when the voltage of the condenser at the end of the period in question is near the voltage to which it is discharging, the slope of the curve will be small. Therefore, small changes in voltage will cause large changes in the time of discharge. Hence, for good frequency stability we should have a large value of slope

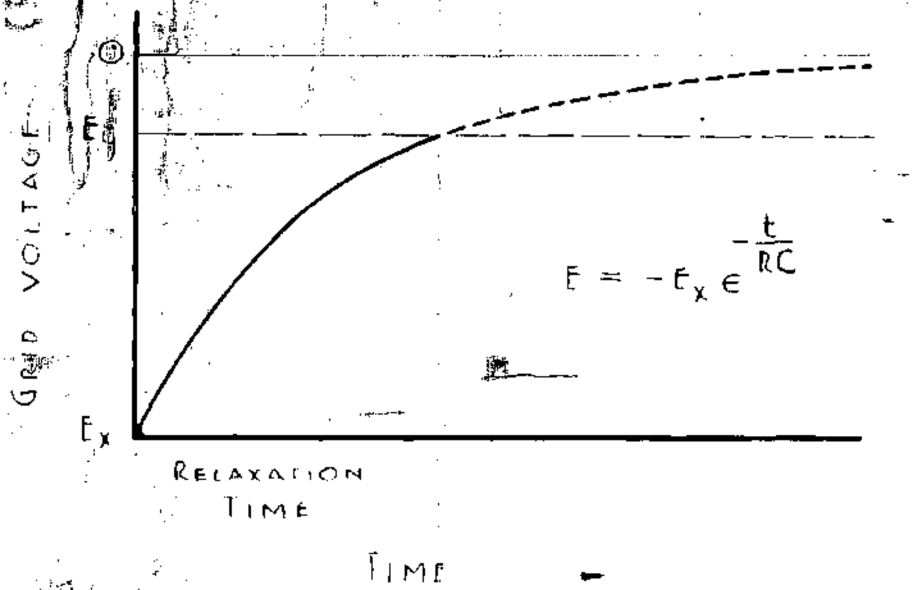

FIGURE 7

EXPONENTIAL RISE OF GRID VOLTAGE WHEN GRID-LEAK IS GROUNDED

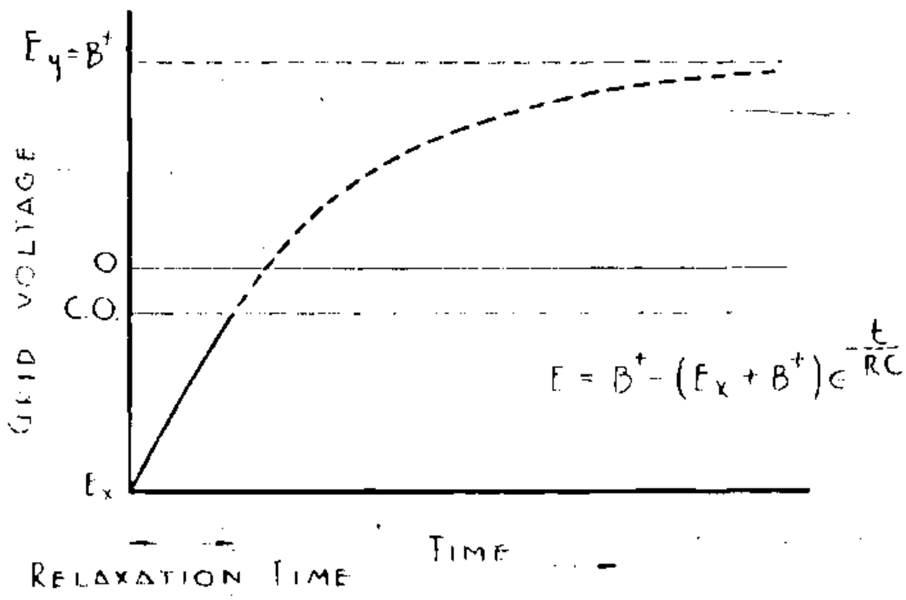

FIGURE 8

EXPONENTIAL RISE OF GRID VOLTAGE WHEN GRID-LEAK IS RETURNED TO B^+

in the vicinity of cut-off in the voltage curve. This may be accomplished in two ways. First, we may make the cut-off voltage as far below ground as possible. This can be done by using a tube with a low value of μ, since

$$V_{cut\text{-}off} = \frac{E_b}{\mu} \qquad (7)$$

Second, we may return the grid-leaks to some positive voltage rather than to ground. The latter is the most effective and was used in this thesis for this reason and because other considerations required a tube with a high gain rather than a low one. Referring to Figure 8 it can be seen that the grid voltage curve between E_x and cut-off is almost linear and approaches the cut-off value at a much greater angle than does the corresponding curve of Figure 7. As stated above, this considerably increases the frequency stability of the free-running multivibrator and it will be shown later that it also aids greatly in synchronized multivibrators.

Synchronization of Multivibrators

In the foregoing discussion of the free-running multivibrator, we have seen, by the relation of equation (1), how the frequency of the multivibrator is determined by the time required for the grid voltage to relax to the value of tube cut-off voltage. Obviously, then, we should be able to control this relaxation time by adding to, or subtracting from the grid voltage some externally injected voltage. Figure 9, page 23, shows how the superposition of a sine wave upon the grid voltage can control the period of a multivibrator. The most reliable control is established when the free-running period is about five per cent longer than the period of the frequency to which it is to be synchronized.[9] Thus the injected voltage causes the grid voltage to reach cut-off before it ordinarily would.

From Figure 9, page 23, it can be seen that if the amplitude of the sine wave were reduced sufficiently and its frequency were doubled, we could superimpose one complete cycle of the injected signal on the grid voltage wave before cut-off was reached. Therefore, by exercising amplitude control of the injected voltage we can obtain frequency division. The multivibrator will lock in at some sub-multiple of the synchronizing signal, the order of division being determined by the amplitude of the injected voltage and, as will be shown next, by the manner of injection.

We will now show that in order to divide by an even number we must feed the synchronizing signal to the two grids in time phase, and to divide by an odd number we must feed the two grids 180 degrees out of phase.

If the order of division is to be even, there will be superimposed on each half cycle of grid voltage one or more complete cycles of the synchronizing signal as shown in Figure 10, page 23. For divisions of 2, 4, 6, 8, or 10, the multivibrator grid voltage half cycle will show 1, 2, 3, 4, or 5 complete cycles, respectively, of the injected voltage upon it.

Let us take for example a division by two as is done in the first multivibrator stage. As stated above, there will be one complete cycle of the injected signal on the wave shape of grid number 1. Now since

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[9]E. R. Shenk, *op. cit.*

there must be a total of two cycles of the synchronizing signal for each cycle of the multivibrator, the remaining cycle must appear upon the second half period of the driven multivibrator. By again referring to Figure 10, it is obvious that both grids should be fed in phase in order that there will be two full cycles of the higher frequency within each cycle of the lower.

The same reasoning holds for odd number division except that there will be an odd number of half cycles of the synchronizing signal for each half cycle of the driven multivibrator. For divisions of 1, 3, 5, 7, or 9 there will be respectively 1, 3, 5, 7, or 9 half cycles superimposed on the grid voltage wave. By referring to Figure 9, it can be seen that only when the grids are fed 180 degrees out of phase can this occur.

Unfortunately we are not able to say that in-phase voltage injection always gives even order division and that out-of-phase injection always gives odd order division. We can only say that there is a strong tendency to do so. This is true because it is impossible to build a multivibrator which is absolutely symmetrical and so long as there is the slightest amount of asymmetry there need not be the same number of cycles of injected voltage upon the two half cycles of the multivibrator. Therefore, the ultimate determining factor is the amplitude of the synchronizing signal. This was repeatedly demonstrated during the construction of the multivibrator system. It is obvious, then, that the greatest stability occurs when the circuit is as close to symmetry as possible.

If the magnitude of the synchronizing voltage is too small, the

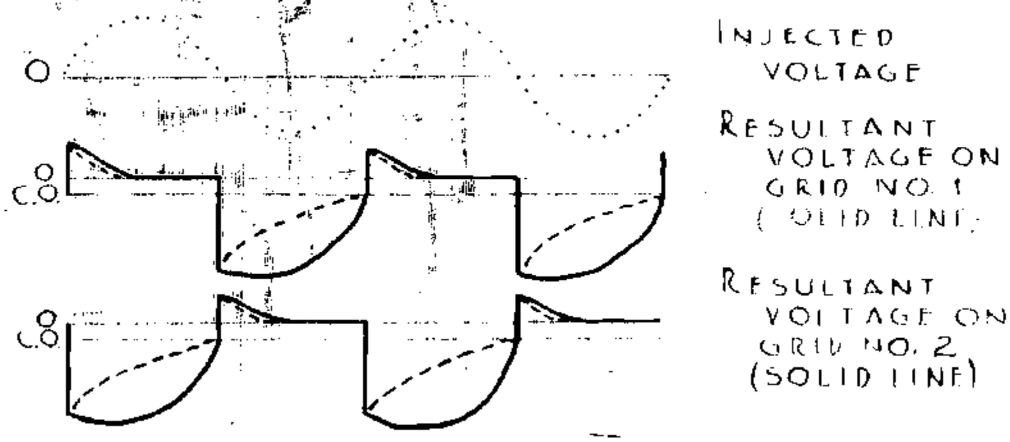

FIGURE 9

SYNCHRONIZATION OF A MULTI-VIBRATOR BY A SINE WAVE OF THE SAME FREQUENCY WHICH IS INTRODUCED INTO THE GRID CIRCUITS 180° OUT OF PHASE. GROUNDED GRID-LEAK RETURN.

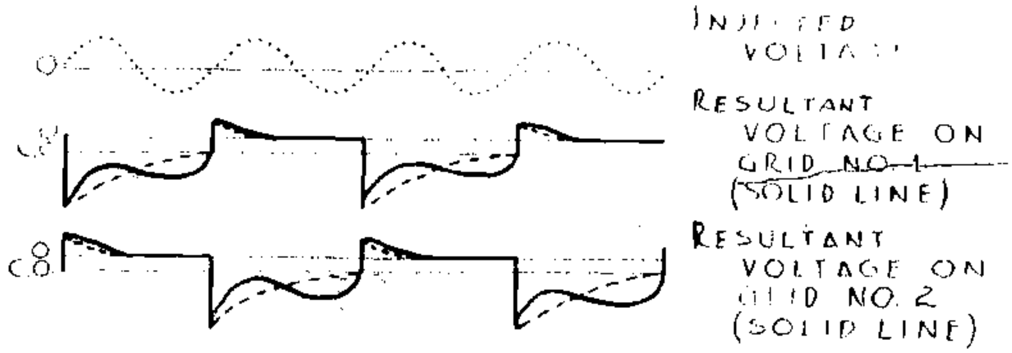

FIGURE 10

SYNCHRONIZATION OF A MULTI-VIBRATOR BY A SINE WAVE OF TWICE THE FREQUENCY WHICH IS INTRODUCED INTO THE GRID CIRCUITS IN PHASE. GROUNDED GRID LEAK RETURN.

grid voltage will not be forced up to the cut-off value soon enough and an excess of one or more cycles of the synchronizing voltage may appear on the grid wave. This would cause synchronization at a frequency lower than that desired, or it is possible that the multivibrator would not synchronize at all. With a synchronizing signal which is too large the grid voltage will be forced to cut-off too soon, causing synchronization at a frequency larger than that for which it was designed. This condition, as well as that of the former, is one of instability, because the free-running frequency would be incorrect for other than the nominal value.

Both Figures 9 and 10 show wave forms of multivibrators whose grid-leaks are returned to ground. It can be seen that with higher orders of division rigid amplitude control of the synchronizing signal must be exercised to prevent the grid voltage from rising to the cut-off value prematurely. When positive grid-leak return is employed, the angle of approach is much greater and the possibility of synchronizing at the wrong frequency is greatly lessened. This is shown in Figure 11.

For reasons of clarity the discussion of synchronization has thus far been limited to the use of sine waves as the synchronizing voltage. Actually, there is only one such occurance in this thesis, i.e., the synchronization of the 50 kc multivibrator by the 100 kc standard oscillator. In all the other cases each multivibrator is synchronized by the preceeding stage. Consequently, since the output of a multivibrator is fundamentally a square wave, we are more interested in synchronization by this voltage than with a pure sinusoid. However, there is no basic

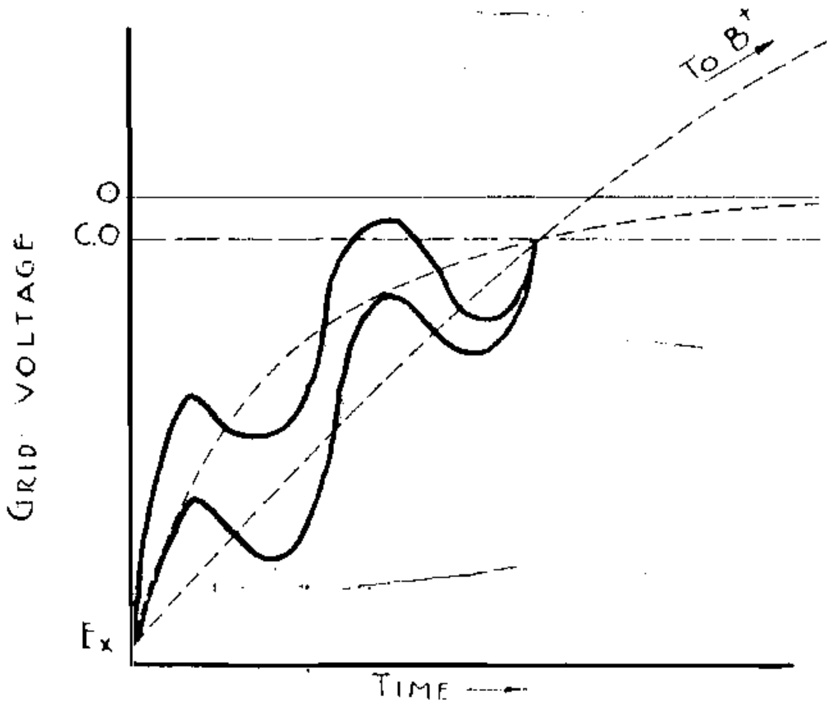

FIGURE 11

SUPERIORITY OF POSITIVE-GRID-LEAK RETURN OVER GROUNDED GRID-LEAK RETURN FOR MULTIVIBRATOR SYNCHRONIZATION difference and the techniques employed in sine wave synchronization may be used successfully where square waves are involved. Actually, square waves are somewhat better for synchronization than sine waves because the instantaneous rise in voltage at the leading edge of the wave causes the grid voltage wave to approach the cut-off value at approximately 90 degrees.

Multivibrator Design Characteristics

The tube used in all five multivibrator circuits is the 6SC7. This is a dual triode which was chosen for its high gain and low plate current drain. The high gain was desired principally because it helps inherent frequency stability. However, maximum gain was not realized in every case because a low plate load resistor was necessary to preserve the desired wave shape. In other words, if the charging circuit of the condensers has a high resistance, then the switching action will not be nearly instantaneous and the forward part of the plate voltage wave will be rounded off. It was desired to strike a medium between high gain and square wave output.

The synchronizing voltage for each successive stage was secured from the previous stage by capacitive coupling. The size of the coupling condenser determines the amplitude of the synchronizing signal. In-phase injection is accomplished by capacity coupling the two grids of the driven multivibrator to one plate of the driver stage. Out-of-phase coupling is secured by connecting the coupling condensers separately to the two plates of the driver stage; this is in effect a push-pull arrangement.

The 50 kc multivibrator is synchronized by in-phase injection of a signal fed from a buffer amplifier on the Meacham oscillator chassis through a co-axial line to the coupling condensers on the multivibrator chassis.

As stated above all of the multivibrators employ positive grid-leak return. In this case the grid leak resistor is connected between the grid and the plate supply lead. Since the grid relaxes toward a voltage that is 200 volts above ground, the portion of the grid wave curve between the original high negative value and the cut-off voltage of the tube is practically a straight line with a relatively steep slope.

The free-running frequencies of the multivibrators are not all controlled in the same way. The 50 kc and the 10 kc multivibrators have their relaxation time adjusted by varying the capacitance in equation (5). Both condensers are variable in these two circuits. This form of control was chosen because the size of condensers necessary at these frequencies is easily obtainable in variable types. The free-running frequencies of the three remaining multivibrators are controlled by potentiometers in the grid leak circuit, since the condensers used at these frequencies are relatively large.

The buffer amplifiers for the 10 kc, 2 kc, and .4 kc signals all use 6SC7 tubes in a conventional resistance coupled circuit. The input of each amplifier is capacitively coupled to a plate of its respective multivibrator. The 50 cycle multivibrator drives a 6L6, class A_1, impedance coupled power amplifier which delivers approximately two watts at 115 volts to the clock. The impedance consists of a high inductance partially resonated by a condenser.

The system of frequency division used in this thesis has one inherent weakness, i.e., incorrect division. If any one of the five multivibrators fails to synchronize at its assigned frequency, the clock will indicate incorrect time without any indication of the failure of the system. The multivibrators as a whole are quite stable, however, and if they are all properly adjusted the system will function as designed.

FREQUENCY CALIBRATION

If we again refer to the relation given by equation (1), we see that our frequency measurements are based on the time interval of the standard second. Because the ultimate time standard is the rotation of the earth once per sidereal day we must have a relation involving mean solar seconds and sidereal seconds. This difference in times is caused by the fact that the earth revolves with respect to the vernal equinox one more time in a solar year than with respect to the sun, due to the earth's moving around the sun once in a year. Precision observation has shown that the sidereal unit of time is shorter by 0.99263 than the corresponding unit of mean solar time. Thus, if we wished to check the frequency of the standard by means of the meridian transit, this factor would enable us to readily convert the interval between successive transits to a mean solar day.

This method of calibration, however, is impractical outside of an astronomical observatory. Consequently, the standard second as broadcast by station WWV will be considered as basic for calibration purposes. For this reason the frequency standard system includes both a 2,000 cycle signal and a 50 cycle clock so that ready comparisons may be made with the Bureau of Standards.

The clock is designed to keep true time when operated from exactly 50 cycle excitation. The multivibrator circuits step the oscillator frequency down by a factor of 2,000 to 1 to drive the clock. It is therefore evident that it will keep true time if the standard oscillator is exactly 100,000 cycles, and one second on the clock will count 100,000 oscillations of the crystal circuit. If the clock gains on true time, the crystal is oscillating at a frequency greater than 100 kc, and the percentage gain is the same as the percentage that the crystal frequency exceeds 100 kc. The gain or loss in seconds for a period of 24 hours multiplied by 1.1574, the ratio of 100,000 to 86,400 (there are 86,400 seconds in 24 hours), added to or subtracted from 100,000 gives the average frequency of the standard for the 24 hour period. Or conversely, if the standard oscillator is in error by one cycle then the clock will be off by 1/1.1574 or 0.8651 seconds at the end of 24 hours. This leads to a rather serious failing of this system of measurement with regard to highly stable oscillators. Assume that the oscillator is at variance with the true frequency by one part in a million, an error 0.10 that of the previous case. Then the clock would require 8.6 days to vary by one full second. This would lead to rather difficult comparison problems.

Despite the above named handicap, the clock affords an excellent device for integrating the errors of the oscillator over a long period.

Short time checks of frequency are easily obtained by making use of the 2,000 cycle multivibrator output. This signal is compared with the 4,000 cycle tone as broadcast by the Bureau of Standards. The simplest method of making this comparison uses Lissajous figures displayed on the screen of an oscilloscope.

If two signals of identical frequency are applied to an oscilloscope, one signal to the X axis and the other to the Y axis deflection plates, then a 1 to 1 Lissajous figure will be described on the screen. This figure will not move if the frequencies are the same. However, if the frequencies differ the figure will appear to revolve on the screen. If the frequency difference is exactly one cycle per second, then the figure will describe one revolution per second. One revolution every five seconds would mean a frequency difference of 1/5 cycle per second, and so on.

A similar method permits us to compare two frequencies which approximate an integral ratio. Let the standard frequency of 4,000 cycles be placed on the X axis of the scope and an unknown signal placed on the Y axis. Assume that a 1 to 1 Lissajous figure is formed and that it rotates twice per second; its frequency of rotation then tells us that the unknown is either 4,002 cycles or 3,998 cycles. It is now obvious that had the unknown been 2,001 cycles or 1,999 cycles there would have been a 2 to 1 Lissajous with the same frequency of rotation of one cycle per two seconds. Now in the calibration of the standard oscillator we are to compare a 2,000 cycle signal with a 4,000 cycle standard by means of a 2 to 1 Lissajous figure. Knowing that the number of revolutions per second of the figure divided by two will give the amount of variance between the frequency of the 2,000 cycle multivibrator and the nominal value, we can easily calculate the actual value of the multivibrator frequency.

To illustrate, again assume that the standard oscillator is off frequency by one part in a million, or plus or minus 0.10 cycles. The 2,000 cycle multivibrator will then show an error of 0.002 cycles (dividing by 50) and one revolution of the Lissajous figure would require 1,000 seconds, or 16 minutes and 40 seconds. The actual time required may be reduced by measuring the time of half a revolution when 2 to 1 Lissajous are involved.

If the 4,000 cycle signal is known to be exact, the accuracy of this measurement is only dependent on how well the operator can visually detect the completion of a half cycle.

Thus far we have spoken only of frequency differences and have not stated whether the measured difference should be added or subtracted to give the actual frequency. This can be determined with the aid of a moderately stable, variable frequency, audio oscillator. The signal of the variable oscillator is placed on the oscilloscope with the 2,000 multivibrator and the frequency adjusted until the Lissajous figure stands still. Next the 2,000 cycle multivibrator signal is replaced by the 4,000 cycle nominal; if the figure moves, then the frequencies are not the same. If it is necessary to increase the frequency of the audio oscillator to stop the Lissajous figure, then the multivibrator frequency is less than the nominal.

EXPERIMENTAL RESULTS

At the inception of this thesis it was the desire of the writer to design and construct a frequency standard having an extremely high frequency stability. Unfortunately this end was not fully realized for two reasons.

The first of these is the quartz crystal itself. It is a well known fact that the natural resonant frequency of a piezoelectric crystal is dependent upon the temperature to a varying degree in all known cuts. For this reason all high-precision oscillators should have the crystal mounted in an oven so as to minimize the effect of changing room temperatures. It was at first hoped that a GT cut crystal could be obtained as this cut has practically a zero temperature coefficient over the range of probable room temperatures. However, this was not possible and a DT cut crystal was decided upon as next best for our purpose.

The DT cut operates at the desired frequency at only a single temperature. This is shown in Figure 12. Therefore such a crystal should be operated in an oven which holds the temperature at the point of zero slope. Despite the desirability of an oven for this crystal, one was not available for use with this thesis. However, in order that sometime in the future an oven might be incorporated in the unit, the crystal was selected to have zero temperature coefficient at approximately 58 degrees centigrade, a temperature well above the probable room maximum so that the oven need never be refrigerated. By again referring to Figure 12 it will be seen that at normal room temperature, the crystal will vibrate at less that its designed rate of 100,000 cycles per second.

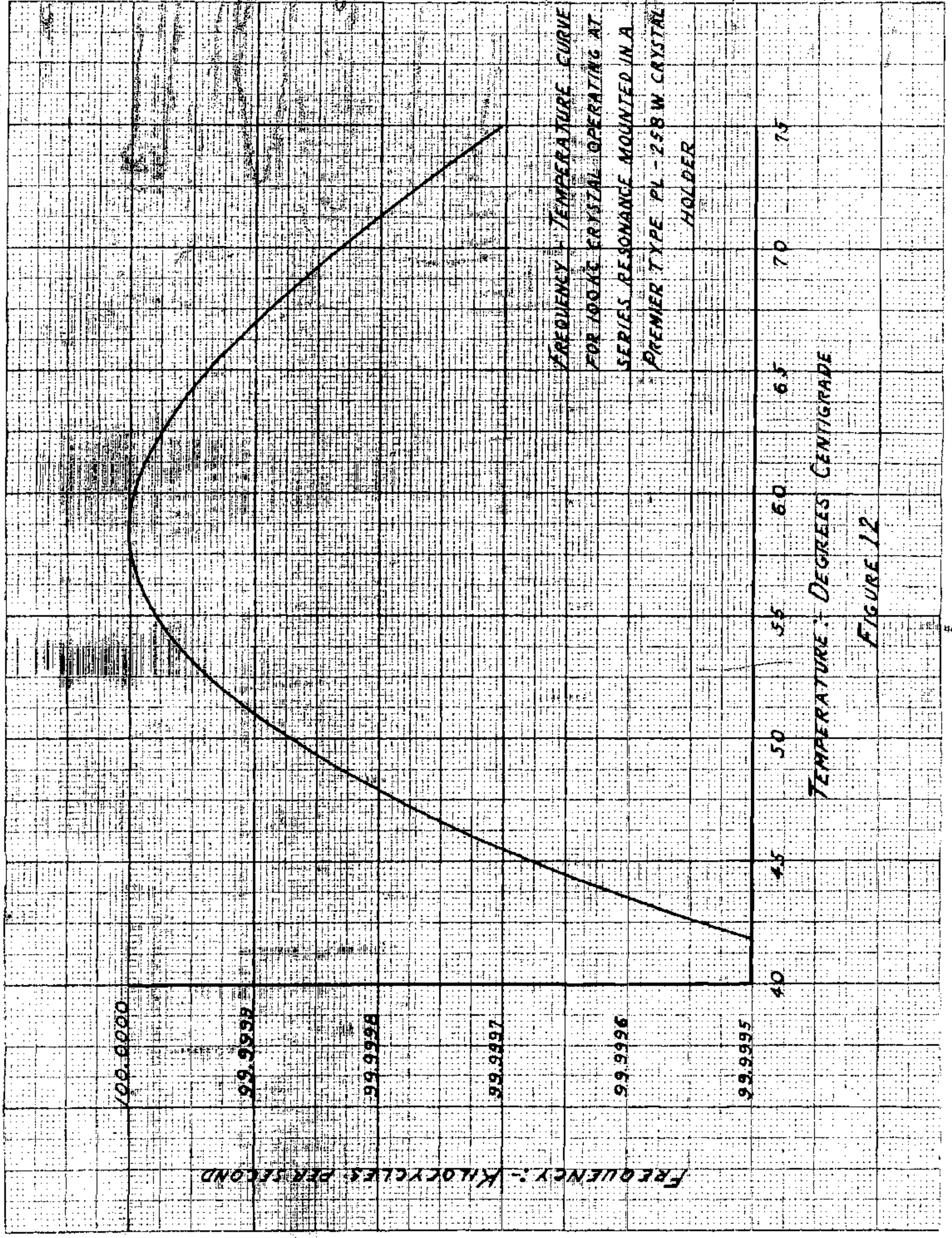
FREQUENCY - TEMPERATURE CURVE
FOR 100 KC CRYSTAL OPERATING AT
SERIES RESONANCE MOUNTED IN A
PREMIER TYPE PL - 258 W CRYSTAL
HOLDER
100.0000
99.9999
99.9998
99.9997
99.9996
99.9995
FREQUENCY :- KILOCYCLES PER SECOND
40
45
50
55
60
65
70
75
TEMPERATURE : DEGREES CENTIGRADE

FIGURE 12

The second reason is the relatively low gain obtained in the amplifier circuit of the oscillator. This was made necessary primarily because of insufficient electrostatic shielding between the primary and the secondary of the output transformer of the second amplifier. The secondary winding was only very slightly unbalanced to ground, but when the gain of the amplifier is increased much beyond 200, instability occurs. It was therefore necessary to limit the gain of the amplifier circuit to approximately 150 by broadening the interstage resonance characteristic and by reducing the voltage at the plate of the amplifier tubes by the use of abnormally large decoupling resistors.

Conditions did not permit frequency calibration over a long period of time and it was necessary to make only short time frequency checks. These tests were made according to the procedure outlined in the previous section and showed that the stability of the Meacham oscillator circuit was in excess of one part in 100,000.

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APPENDICES

APPENDIX I

A MATHEMATICAL ANALYSIS OF THE Q MAGNIFICATION OF THE MEACHAM OSCILLATOR BRIDGE NETWORK

This analysis is due to W. A. Edson[12] and is based upon the assumption that the output current of the bridge may be neglected. Figure 13 shows a typical Wheatstone bridge type network as used in the Meacham oscillator and Figure 14 illustrates the associated vector diagram for this network.

In order to simplify as much as possible we will let the voltage across each arm of the bridge be designated by the letters of the respective bridge terminals.

If the frequency is such that the arm CD is exactly resonant, the bridge is entirely resistive and the output voltage BD is in phase with the input voltage AC. The following simple equations describe the system at resonance.

$$AD/AC = R_4/(R_3 + R_4)$$

$$AB/AC = R_2/(R_1 + R_2)$$

$$BD = AD - AB = AC\left[R_4/(R_3 + R_4) - R_2/(R_1 + R_2)\right]$$

This may be simplified by making the substitution

$$R_2 = (1 - \delta)\, R_o$$

[12] W. A. Edson, op. cit., p. 172.

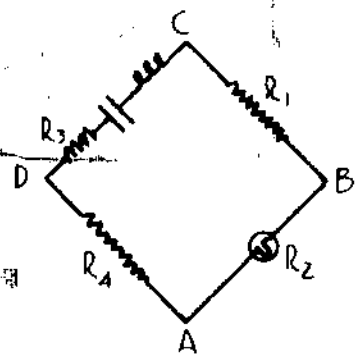

FIGURE 13

MEACHAM OSCILLATOR BRIDGE NETWORK

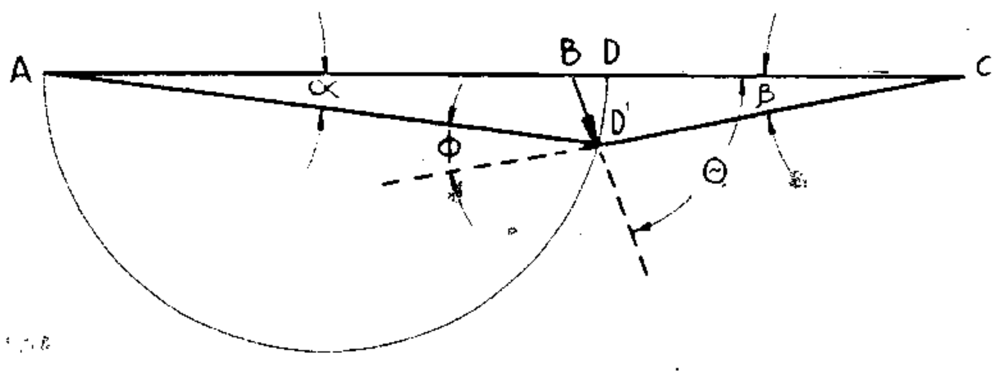

FIGURE 14

VECTOR DIAGRAM OF THE VOLTAGES OF THE BRIDGE SHOWN IN FIGURE 13

Where R_o is the balance value such that

$$R_o R_3 = R_1 R_4$$

Then

$$BD/AC = \frac{1}{\frac{R_3}{R_4} + 1} - \frac{1}{\frac{R_1}{R_o(1 - \delta)} + 1} = \frac{1}{\frac{R_3}{R_4} + 1} - \frac{1}{\frac{R_3}{R_4(1 - \delta)} + 1}$$

Since we are only interested in the performance of the bridge at points very close to resonance, δ is small compared to 1, and $1/(1 - \delta)$ is approximately equal to $1 + \delta$. Therefore

$$BD/AC = \frac{1}{\frac{R_3}{R_4} + 1} - \frac{1}{\frac{R_3(1 + \delta)}{R_4} + 1} = \frac{R_4}{R_3 + R_4} - \frac{R_4}{R_3 + R_4 + \delta R_3}$$

Reducing to a common denominator and cancelling numerator terms there results

$$BD/AC = \frac{\delta R_3 R_4}{(R_3 + R_4)^2 + \delta R_3(R_3 + R_4)} \doteq \frac{\delta R_3 R_4}{(R_3 + R_4)^2}$$

provided $\delta \ll 1$.

At a frequency very slightly higher than the resonant frequency the current through arm CDA lags the voltage and the point D' is displaced from the line AC. If the displacement is very small we may write in radian measure

$$\theta = \tan \theta$$

If this is true we may also write

$$\alpha = \tan\alpha; \quad \phi = \tan\phi; \quad \beta = \tan\beta$$

If the net reactance of the arm CD is equal to X we may write

$$\tan\phi = \phi = X/R_3$$

$$\tan\alpha = \alpha = X/(R_3 + R_4)$$

and

$$\theta/\alpha = AD/BD$$

$$\beta/\alpha = AD/DC$$

A careful consideration of the system shows that ϕ is the phase shift which would have resulted had the tuned circuit been used to control the oscillator without the bridge. With the aid of the bridge network the resulting phase shift is θ. Therefore the advantage secured by the use of the bridge is given by

$$\theta/\phi = (\theta/\alpha)(\alpha/\phi) = (AD/BD)(R_3/(R_3 + R_4)$$

$$\theta/\phi = (AD/AC)(AC/BD)(R_3/(R_3 + R_4))$$

substituting

$$\theta/\phi = \frac{R_4}{R_3 + R_4} \cdot \frac{(R_3 + R_4)^2}{\delta R_3 R_4} \cdot \frac{R_3}{R_3 + R_4} = \frac{1}{\delta}$$

Thus we have shown that as δ is made very small the phase magnification or effective Q magnification is greatly increased.

APPENDIX II

CALCULATION OF PARAMETERS OF A 10 KC MULTIVIBRATOR

Frequency -- 10,000 cycles per second

Tube -- 6SC7

Amplification factor of tube -- 70

Plate resistance of tube -- 53,000 ohms (approximately)

Plate supply voltage -- 300 volts DC

Problem: Find the required load resistance, grid leak resistance, and coupling capacitance.

The approach used here is that of Kiebert and Inglis[13] and it is based upon the simplified equivalent circuit of Figure 15. The condition simulated by this circuit occurs slightly before tube 2 is cut-off.[14] S_1 is open, tube 1 is not conducting and hence its plate voltage, e_3, is the same as the plate supply, or 300 volts. S_2 is closed, tube 2 is conducting and its plate voltage, e_4, is some value less than 300 volts because of the drop in the load resistor, R_2.

If S_2 is opened and S_1 is closed (switching action), current will flow in the dotted circuit of Figure 15. This current flow produces a voltage across R_4 which biases tube 2 beyond cut-off. Actually, when S_1 is closed, S_2 is automatically opened.

[13] M. V. Kiebert, Jr., and A. F. Inglis, op. cit.

[14] Since the 6SC7 has two triodes in one envelope, they will be referred to as tube 1 and tube 2.

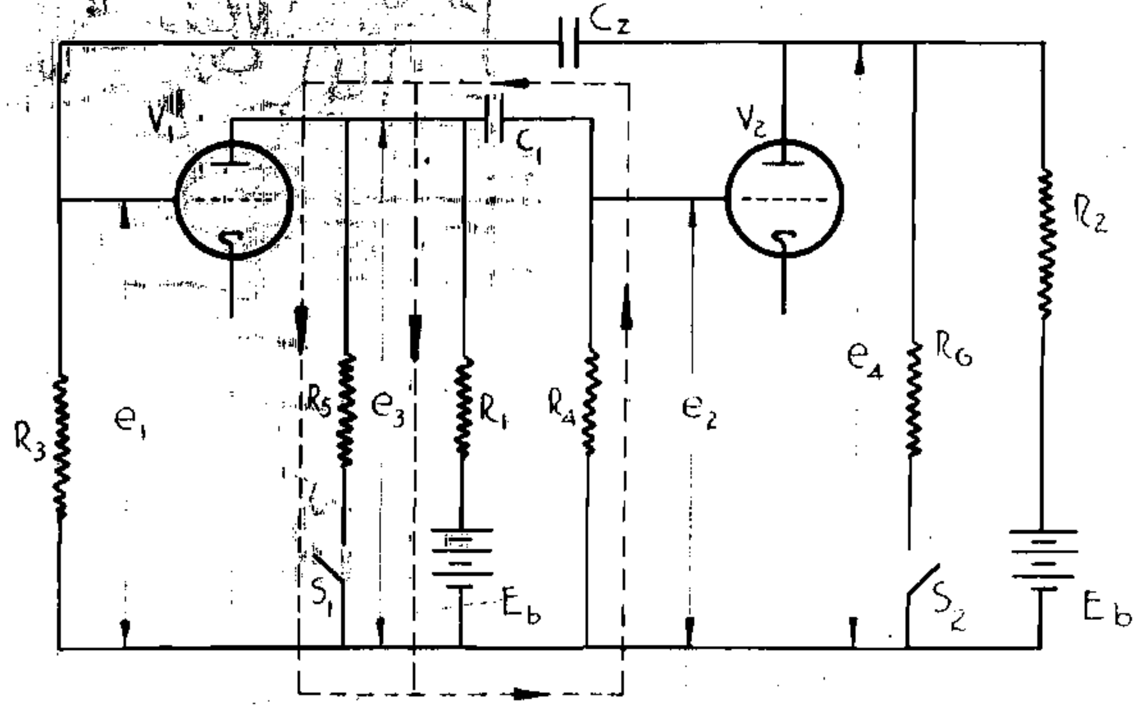

FIGURE 15

MULTIVIBRATOR EQUIVALENT CIRCUIT

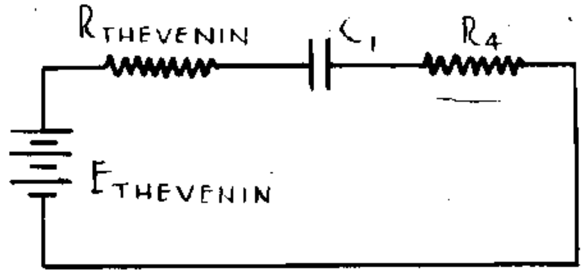

FIGURE 16

EQUIVALENT THEVENIN GENERATOR

Using equation (6) as given in the text we may calculate the approximate cut-off voltage of the tubes.

$$V_{cut\text{-}off} = \frac{E_b}{\mu} = \frac{300}{70} = -4.3 \text{ volts}$$

At this point we will assume values for the plate load and grid-leak resistors, and solve for the coupling capacitance. We must, however, keep in mind certain restrictions when choosing these resistors. First, we want the multivibrator to have as much gain as is possible without too much sacrifice of wave shape. For maximum gain we should use approximately 100,000 ohms in the plate resistor, but this would result in a definite rounding off of the forward part of the plate voltage wave. Therefore, a load of 15,000 ohms was chosen since this value gives moderate gain and fair wave shape. Since the grid leak resistor is the principal resistor in determining the relaxation time of the grid voltage, it will be necessary to make this resistor large if the coupling capacitance is desired small enough so that a variable condenser may be used.[15] With this reasoning let us choose a grid leak resistor of 4 megohms.

Next we will obtain the Thevenin generator to the left of C_1.

$$R_{thev} = \frac{R_1 R_5}{R_1 + R_5}$$

$$E_{thev} = \frac{E_b R_5}{R_1 + R_5}$$

---

[15] See page 18 of this thesis.

$$R_{thev} = \frac{(53)(15)}{68} = 11.7 \text{ Kilohms}$$

$$E_{thev} = \frac{(300)(53)}{68} = 234 \text{ volts}$$

Now let us substitute Figure 16 for the dotted circuit of Figure 15. Also, by examining Figure 15, it can be seen that during conduction in tube 2, a charge accumulates on C_1 until the voltage across it equals the plate supply voltage, since there is no current flowing around the loop involving E_b, R_1, C_1, and R_4.

Since the resistance of the Thevenin impedance is small compared to that of the grid leak resistor, the voltage across tube 1 will be very nearly 234 volts. By Kirchhoff's law the voltage across R_4 (the bias voltage on tube 2) is -66 volts.

Since the bias on tube 2 will now rise exponentially from -66 volts toward the plate supply voltage in 50 microseconds (the time of a half-cycle at 10,000 cycles per second), we may now solve for the value of C_1 which satisfies this condition.

$$t = RC\log_e \frac{E_x}{E_y}$$

$$(50)(10^{-6}) = (8)(10^6)\, C_1 \log_e \frac{(66 + 300)}{(4.3 + 300)}$$

$$C_1 = (34)(10^{-12}) \text{ Farads}$$

Q. E. D.

APPENDIX III

STANDARD OSCILLATOR AND FREQUENCY DIVIDER

SCHEMATIC DIAGRAMS

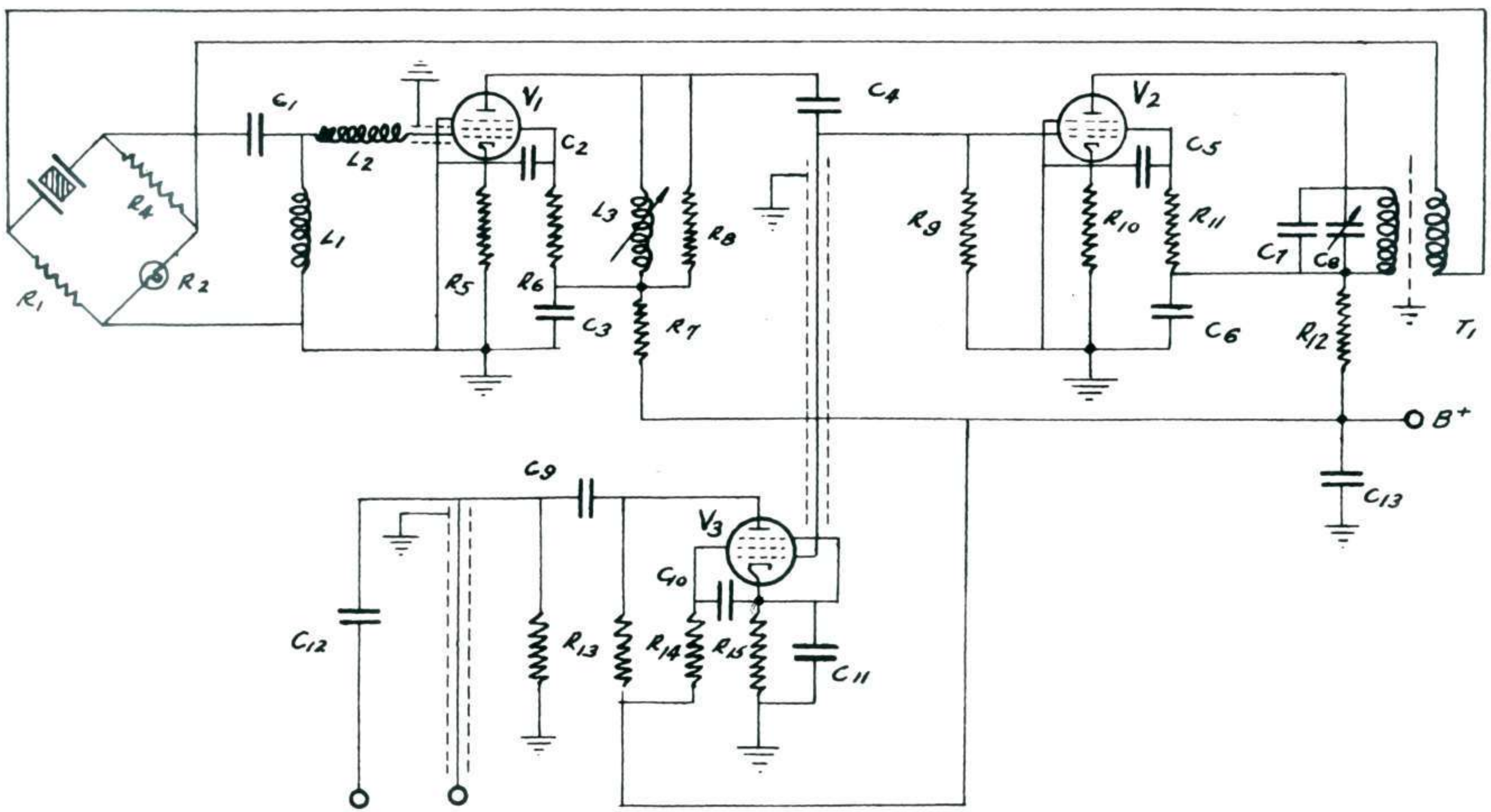

FIGURE 17
STANDARD OSCILLATOR & AMPLIFIER

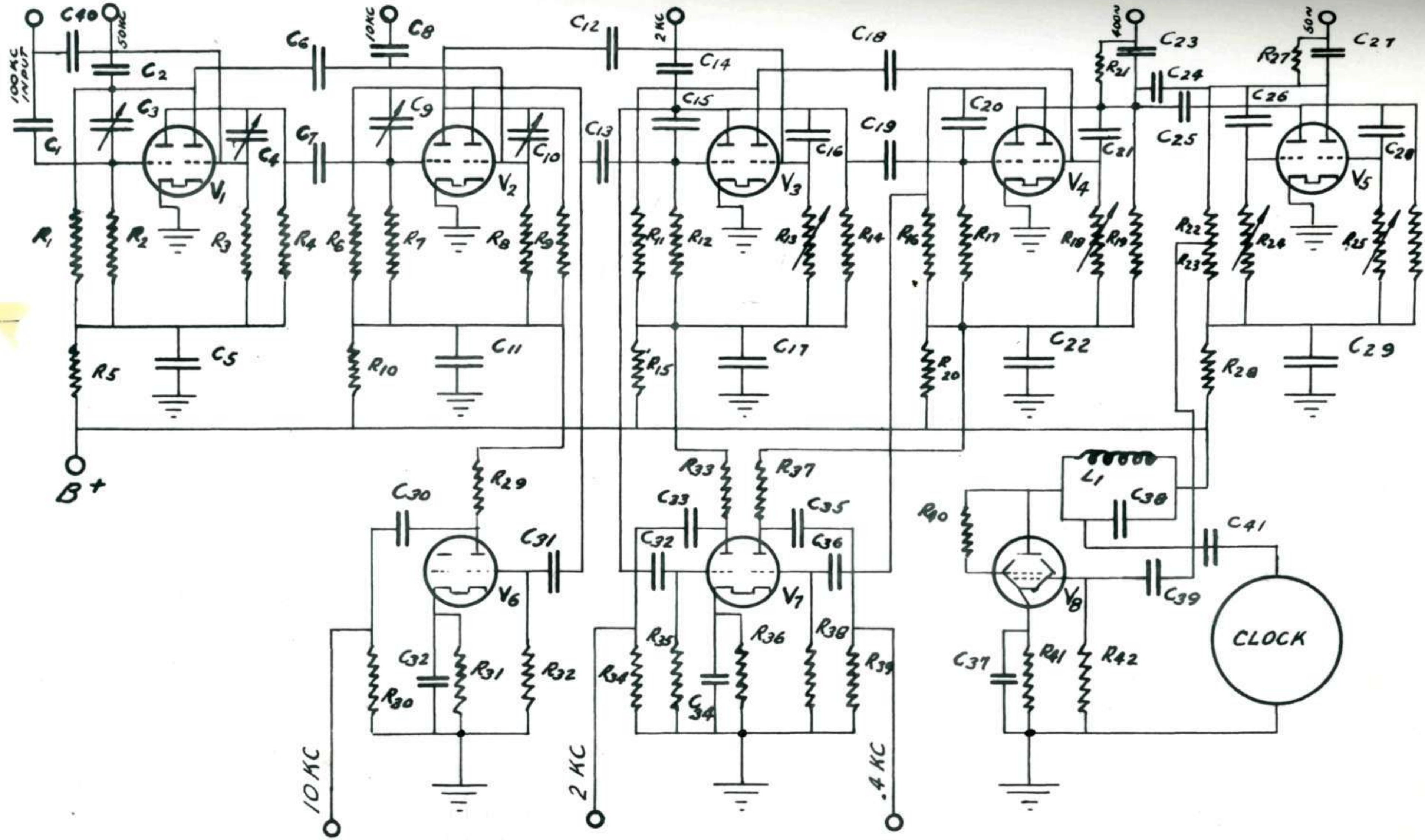

FIGURE 18

FREQUENCY DIVIDER & AMPLIFIERS

APPENDIX IV

CIRCUIT PARAMETERS

THE 100 KC OSCILLATOR AND BUFFER AMPLIFIER

Resistance in Ohms

R_1	44	R_8	4,000
R_4	180	R_9	1,000,000
R_5, R_{10}	1,800	R_{12}	27,000
R_6, R_{11}, R_{14}	250,000	R_{13}	100,000
R_7	24,000	R_{15}	200

Capacitance in Microfarads

C_1	.00184	C_7	.000015
C_2, C_3, C_5, C_6 C_{10}, C_{11}	.01	C_8	.000007 - 45
C_4	.0015	C_9	.00075
		C_{12}	.0000028
		C_{13}	30

Inductance in Millihenries

L_1	1.7	L_3	60-80
L_2	120		

MULTIVIBRATOR CIRCUIT PARAMETERS

Resistance in Ohms

R_1	14,000	R_{17}	3,600,000
R_2, R_3	3,800,000	R_{18}	2,000,000-4,000,000
R_4	17,000	R_{20}	8,000
R_5	2,600	R_{21}, R_{27}	18,000,000
R_6	25,000	R_{22}, R_{23}	30,000
R_7, R_8	8,200,000	R_{24}	2,600,000-3,100,000
R_9	23,000	R_{25}	2,600,000-3,600,000
R_{10}	2,400	R_{28}	6,000
R_{11}	18,000	R_{29}, R_{33}, R_{37}	100,000
R_{12}	2,300,000	R_{30}, R_{34}, R_{39}	460,000
R_{13}	2,500,000-4,500,000	R_{31}, R_{36}	4,600
R_{14}	13,500	R_{32}, R_{35}, R_{38}	1,000,000
R_{15}	4,300	R_{40}	22
R_{16}, R_{19}, R_{26}	57,000	R_{41}	200
		R_{42}	2,500,000

Inductance in Henries

L_1 9

Capacitance in Microfarads

C_1, C_2, C_8, C_{14}, C_{23}, C_{31}, C_{32}, C_{36}, C_{40}	.000005
C_3, C_4, C_9, C_{10}	.000007 - 45
C_5	.1
C_6, C_7, C_{18}, C_{19}, C_{12}, C_{13}	.00000166
C_{11}, C_{17}, C_{38}	.5
C_{15}, C_{16}	.000500
C_{20}, C_{21}	.001000
C_{22}	1
C_{24}, C_{25}	.00000125
C_{26}, C_{28}, C_{39}	.010000
C_{27}	.000100
C_{29}	40
C_{30}	.000170
C_{34}	50
C_{35}	.004600
C_{37}	60

APPENDIX V

PHOTOGRAPHS OF THE FREQUENCY STANDARD AND ITS COMPONENTS

FIGURE 19

FIGURE 20

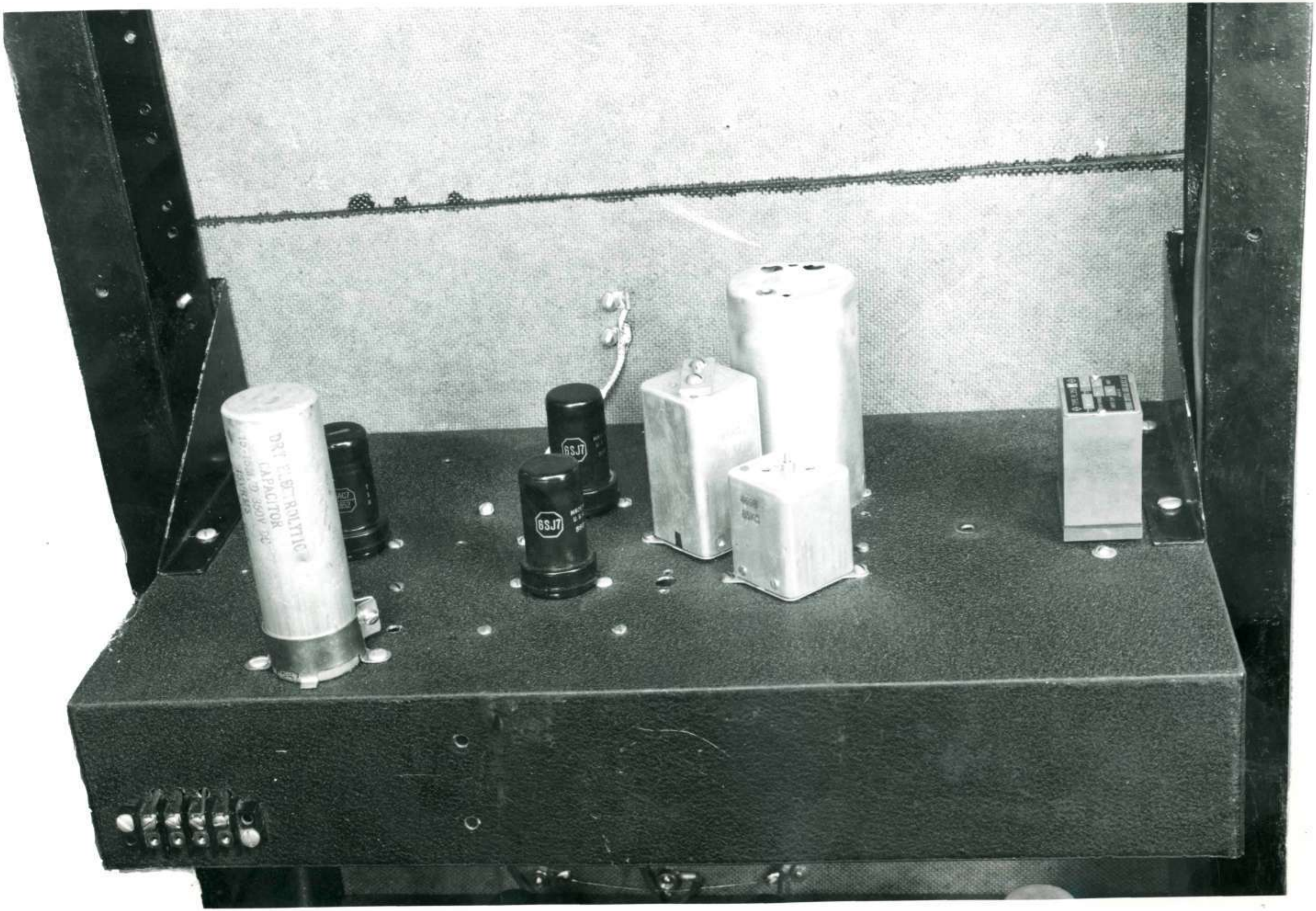

FIGURE 21

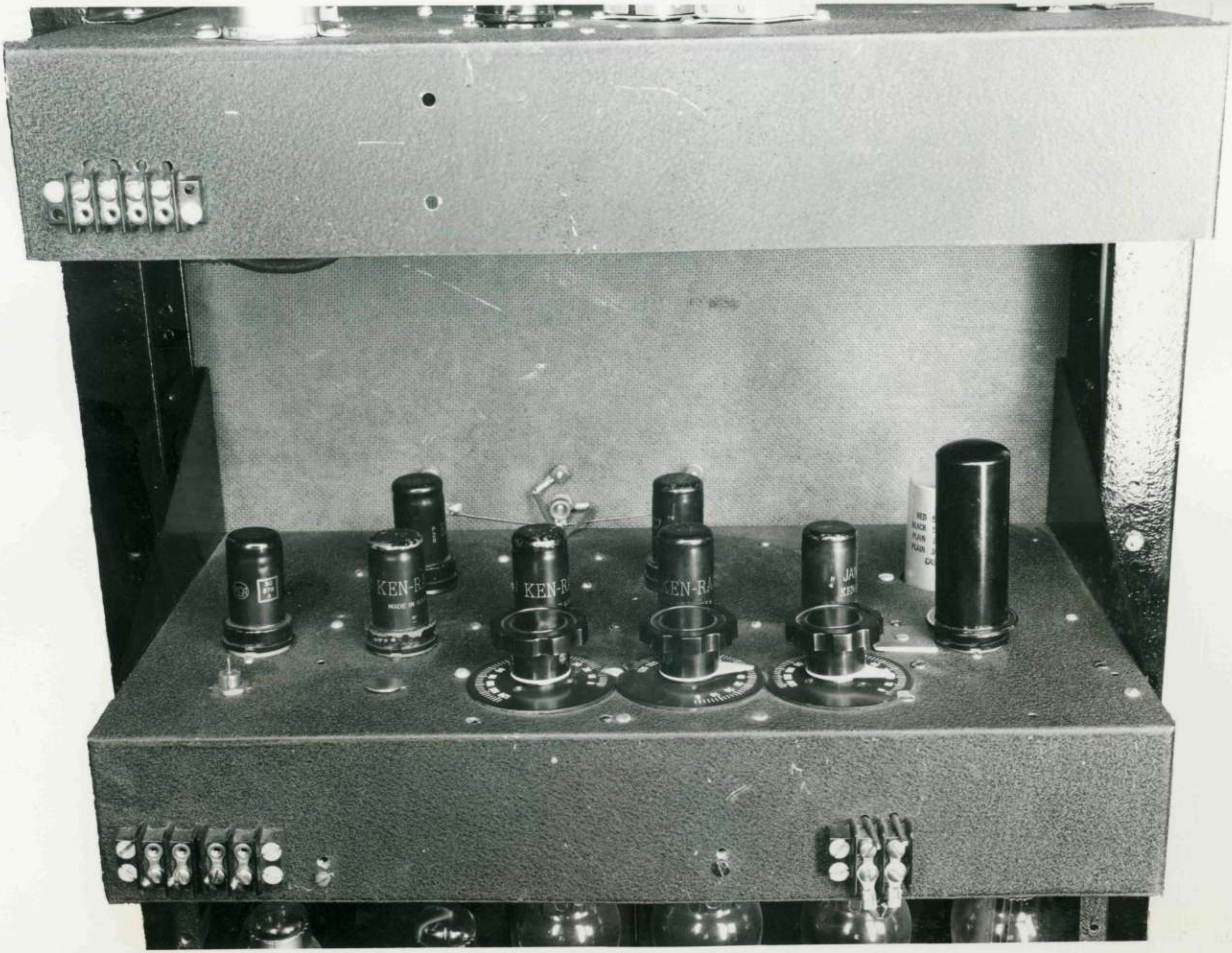

FIGURE 22

APPENDIX VI

OPERATION AND MAINTENANCE INSTRUCTIONS

OPERATION

The frequency standard may be operated from any regulated power supply that is capable of delivering 75 or more milliamps at 300 volts DC and 4.5 amperes filament current at 6.3 volts AC.

The power leads of the standard oscillator and the frequency divider are connected in multiple by means of the terminal strips on the rear of the chassis. The power supply should be connected to the terminal strip on the frequency divider with the filament leads in position 1 and 2, the B supply wire in 3, and the ground wire in position 4. The B supply lead is white; all others are black.

When connecting the frequency standard for operation after an extended period of idleness, an ammeter should be placed in the B supply lead and the voltage increased in increments up to the specified value of 300 volts. At this voltage the total DC current should be approximately 68 mils. This precaution should be taken because of the possibility of a short circuit in the wiring or a bad electrolytic condenser.

Before attempting synchronization, about thirty minutes should be allowed for warming up. During this time the clock will probably operate at the free-running frequency of the 50 cycle multivibrator. This will cause it to read somewhat slow. Synchronization can be accomplished with the aid of a variable frequency oscillator with a range of from 50 cycles to 100 kc. A suitable oscillator for this purpose is the Hewlett-Packard 200-C.

The Standard oscillator should be checked to see that it is performing properly. This may be done by connecting the 100 kc front panel terminals to an oscilloscope. The wave as seen on the scope should be perfectly sinusoidal, but it may have considerable fuzziness as rather high scope gain is required because of the very small signal obtained from the terminals. Next the variable frequency oscillator should be used to check the frequency by means of a Lissajous figure.

After the performance of the standard oscillator has been checked and found satisfactory, it is next necessary to synchronize each of the five multivibrators in sequence, starting with the high frequency one. These tests are facilitated by the use of the test lead provided with the oscillator. This consists of a three foot wire with a spade on one end and a banana plug on the other. The scope is grounded to the multivibrator ground and the spade end of the test lead connected to the upper Y axis terminal of the oscilloscope. The banana plug is then used to connect the various terminals on the front and underside of the frequency divider to the scope.

Continuing with the multivibrator synchronization, the frequency of the 50 kc multivibrator should be checked with a Lissajous figure, using the voltage obtained from the plate terminal underneath the chassis. This frequency should be correct as the 50 kc multivibrator synchronizes readily and no adjustments are intended to be made. However, if after the system is thoroughly warmed up and it has not yet synchronized, reference should be made to the maintenance section of this thesis before attempting any adjustments.

The above also holds for the 10 kc multivibrator as it is almost identical to the preceeding stage and was not intended to require adjustment by the operator. The 10 kc signal may be obtained either from under the chassis or from the terminal on the panel.

In order to check the 2,000 cycle stage, we may leave the variable frequency oscillator set at 10 kc. If a 5 to 1 Lissajous is obtained, then this stage is synchronized. However, if synchronization does not exist, the potentiometer on the rear of the chassis should be adjusted until a 5 to 1 Lissajous figure is formed. The potentiometer should be set in the center of the range over which synchronization is obtained.

The same procedure applies to both the 400 and 50 cycle multivibrators and should be carried out if necessary.

MAINTENANCE

Power Supply

A regulated power supply must be used in conjunction with this frequency standard. Requirements are 75 mils at 300 volts DC and 4.5 amperes at 6.3 volts AC.

Standard Oscillator (Bridge Network)

The bridge consists of a DT cut quartz crystal, two fixed resistors, and a tungsten lamp. Under normal operating conditions the input voltage to the bridge circuit should be .25 volts and the output should be .0045 volts. The most likely trouble here is the possibility of the lamp leads breaking off inside the metal sleeves to which they are soldered. Additional lamps are available from Western Electric Co. as model E-1 switchboard lamps.

The crystal should cause no trouble unless it is damaged by moving. This crystal will not operate in a horizontal position.

Standard Oscillator (Main Amplifier)

The input circuit to the first tube is unusual but should cause no trouble. It consists of two resonant loops, the first of which places C_1 and L_1 in series resonance at 100 kc. The second loop consists of L_1 plus L_2 in parallel resonance with the input capacitance to the tube. The overall gain of this network is approximately 40. The co-axial conductor between L_2 and the grid connection is necessary to obtain the correct value of input capacitance for resonance. L_2 has two taps which are not used at one end of the coil.

The first stage is a simple inductance coupled amplifier with one exception -- R_8 is strapped across the inductive load to broaden the band width and reduce the gain to a point where spurious oscillations would not occur. The inductance, L_3, may be varied by means of the powdered iron core. R_7 is large so as to reduce the voltage on the plate of the tube; this is also true of R_{12} in the second amplifier.

The second stage is also a conventional amplifier with a tuned LC load. The inductance is the high side of a transformer having an electrostatic shield between the windings. C_8 may be varied and should be so adjusted to give the highest possible output voltage without setting up spurious oscillations. The step-down ratio of the transformer is approximately 50.

The tubes used in both stages of amplification in the oscillator circuit are 6SJ7's.

Standard Oscillator (Buffer Amplifier)

A conventional resistance coupled amplifier employing a 6AC7 tube is used to supply the frequency divider. This amplifier has two output terminals, one for driving the multivibrator and one for measuring purposes. The latter is brought out to the front panel on terminals. This signal is quite small as the coupling condenser is 2.8 micromicrofarads. This was done to prevent increasing the capacitance to ground and lowering the gain of the amplifier. The connection to the frequency divider chassis is made by the co-axial cable; this expedient was also incorporated to keep the capacitance at a minimum. One source of trouble here may be in the cable itself. It was necessary to solder the center conductor at the coupling and then wrap the cable with friction tape; undue handling may cause an open circuit in the cable. The voltage as measured at the end of the co-axial cable with a vacuum tube meter having an input of 8 micromicrofarads is approximately 35 volts.

<u>50 kc Multivibrator</u>

This multivibrator, as do the remainder, uses a 6SC7 dual triode in an approximately symmetrical circuit. Its free-running frequency is controlled by the condensers C_3 and C_4 which have screw driver adjustments. These condensers consist of two cermic discs with silver plating on half of each. The capacity is determined by the relative positions of the silvered portions. Close examination will reveal which lead is connected to the stator. Turning the silvered portion of the rotor <u>toward</u> the stator lead <u>increases</u> the capacitance.

The synchronizing voltage injected into the grid circuit is constant in amplitude and has been predetermined so as to cause synchronization when the free-running frequency of the multivibrator is of the proper value (approximately 5% less than 50 kc). Thus the approach to synchronization used here is that of adjusting the free-running frequency of the multivibrator and not by varying the amplitude of the injected voltage.

As has been stated in the text, synchronization occurs most readily when the circuit is symmetrical. Consequently, both C_3 and C_4 should be adjusted equally if possible.

If it becomes necessary to make circuit element changes in any of the multivibrators, and they subsequently fail to synchronize by ordinary means, it may be necessary to make additional changes to bring the circuit into symmetry at a frequency 5% below the nominal. If the multivibrator immediately following the circuit in which changes were made fails to synchronize, then it is probable that the magnitude of the injected signal has changed. It will then be necessary to increase or decrease the capacity of the injection circuit so as to regain the original synchronizing voltage.

The 50 KC terminal under the chassis is connected to the plate of the tube by a 5 micromicrofarad condenser in order that the circuit will not be disturbed when measurements are made at this terminal. When the multivibrator is properly synchronized, the wave shape at this terminal is that shown in Figure 23, page 66.

10 Kc Multivibrator

This multivibrator differs from the 50 kc multivibrator in only two respects (other than the circuit values); these are odd order synchronization and the addition of a buffer amplifier. The buffer amplifier is a simple resistance coupled stage using one half of a 6SC7. It is this amplifier that feeds the front panel terminal, giving the wave shape shown in Figure 24, page 67, under normal operating conditions. The wave form as seen at the plate terminal under the chassis is shown in Figure 23. The synchronizing circuit is different from that of the preceeding stage in that it introduces the voltages to the grids 180 degrees out of phase, whereas the 50 kc multivibrator uses in-phase injection.

2 Kc Multivibrator, 0.4 Kc Multivibrator

These two multivibrators will be discussed together since they are identical in almost every respect. These differ from the two described so far, primarily, in that the free-running frequency is controlled by adjusting the grid-leak resistance instead of the condenser. Both these circuits will be somewhat asymmetrical because there is a variable resistance in only one of the two grid-leaks. Consequently, these circuits are more critical than the preceeding ones and care should be taken to set the resistances in the mid-range of synchronization.

50 Cycle Multivibrator

This is by far the most critical circuit in the entire system, principally because it divides by the largest number. The free-running frequency is controlled similarly to the 2,000 cycle and 400 cycle multivibrator except that a variable resistance is inserted in both grid-leaks. Usually it is necessary only to adjust one of these, namely, the one on the top of the chassis. However, if synchronization is difficult to obtain, it may be necessary to adjust the potentiometer under the chassis.

It was found during construction that better synchronization was obtained when the 400 cycle signal was introduced into the plate circuit rather than that of the grid. Consequently, this variation was incorporated in the final multivibrator. In-phase injection is used as with the 50 kc multivibrator.

The input to the power amplifier is taken from the mid-point of one of the plate resistances. The amplifier uses a 6L6 operated A_1 with a 9 henry load. The clock is connected across this load impedance in series with an electrolytic condenser to block the DC. The amplitude of the output voltage is controlled by partially resonating the inductive load with condenser C_{38}. This also serves to improve the wave shape somewhat.

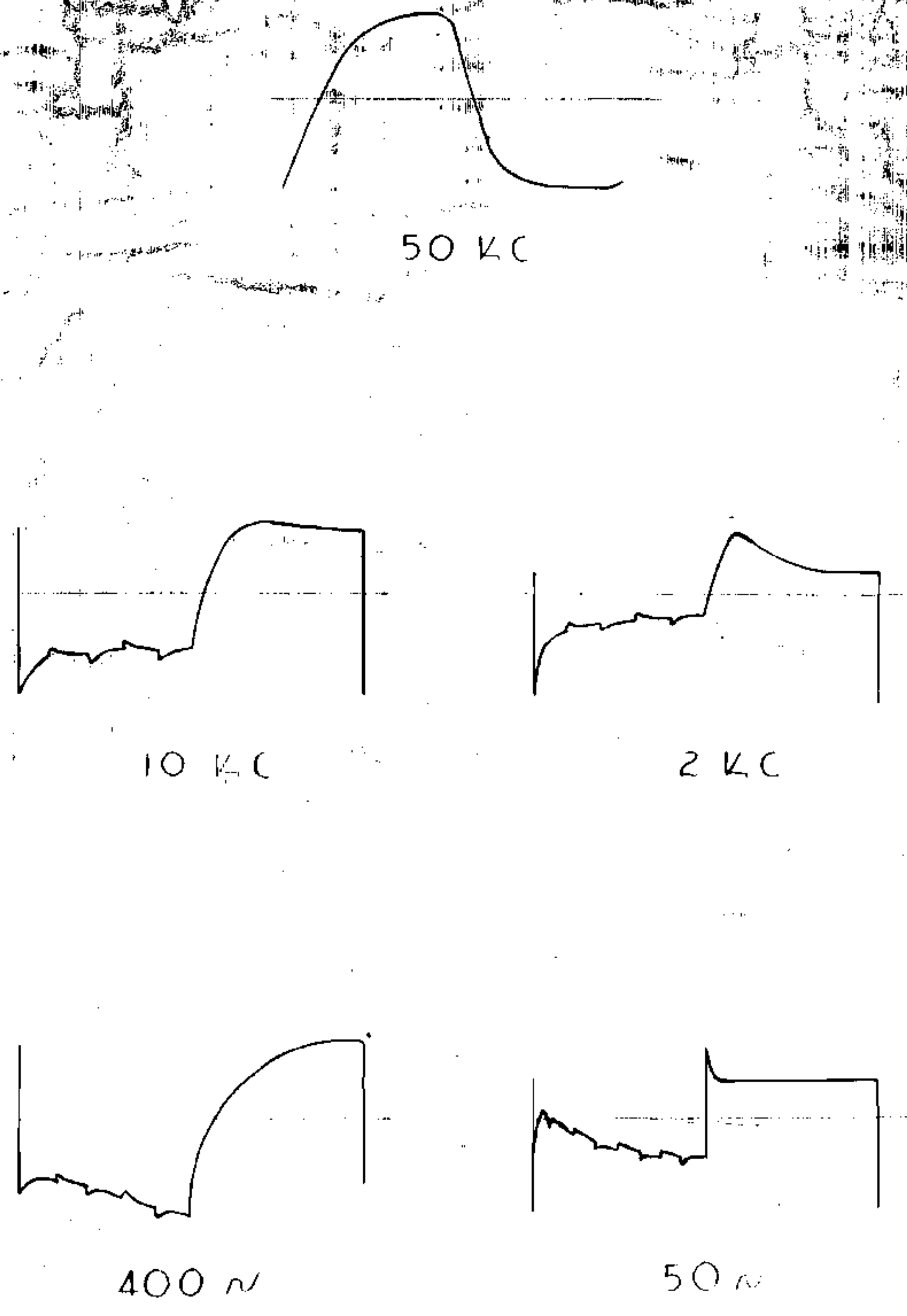

FIGURE 23

MULTIVIBRATOR WAVE SHAPES AT PLATE TERMINALS

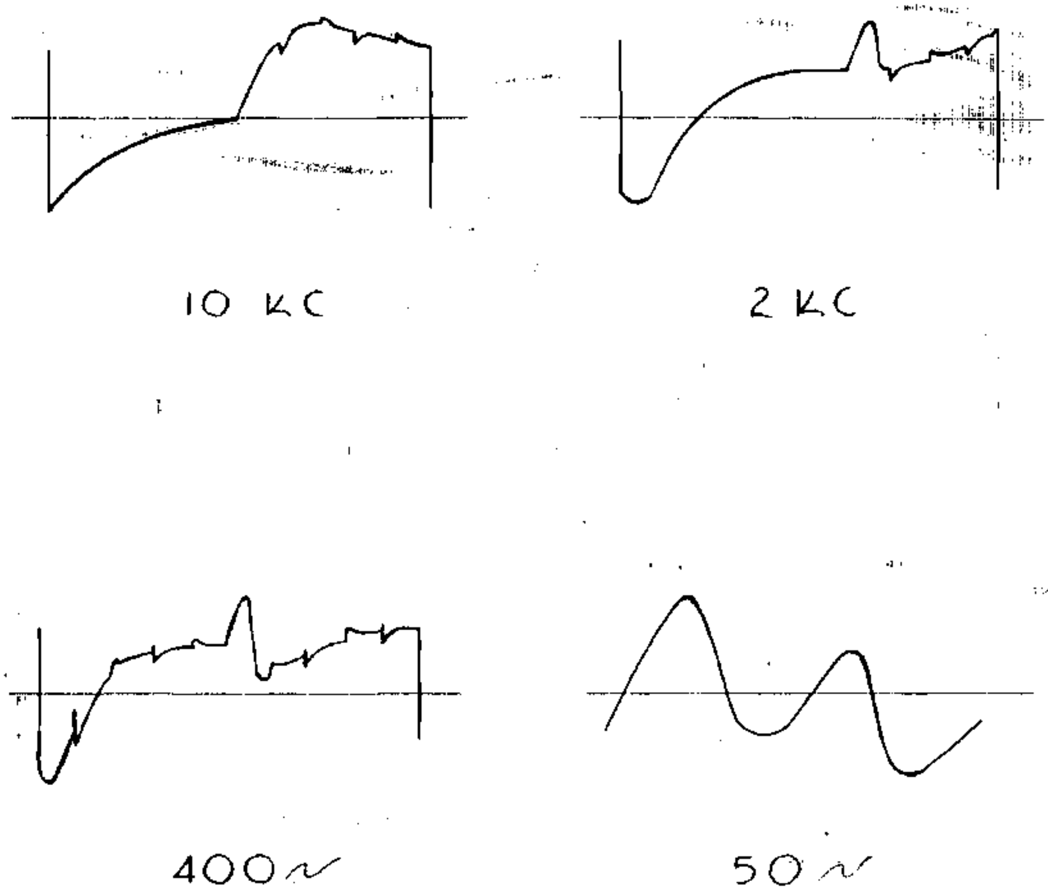

FIGURE 24

MULTIVIBRATOR PLATE WAVE ~~FORMS~~ AS SEEN AT THE TERMINALS OF THEIR RESPECTIVE AMPLIFIERS